

## NOTES ON THE MANUFACTURE AND UPKEEP OF MILLING CUTTERS.

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Although the system of manufacture of milling cutters detailed in this Paper is suitable for general application, it has been developed more particularly to meet the difficulties of extending the use of high-speed steel to milling cutters of complicated shape, required when cutting to give an accurate finish and a good surface. It is believed that these difficulties have been commonly met with, and that owing to them the general introduction of high-speed steels of the Taylor-White class has, so far, generally proved of less benefit to engineers for milling cutters than for any other form of cutting tool used in engineering workshops.

Perhaps the advantages to be obtained by the use of high-speed steels for such cutters are also not so obvious as they are for the heavy lathe or planer tools, where the almost red-hot chips, that they can be made to produce, appeal to the least observant onlooker. When, however, it is considered that this class of steel not only has the property of keeping a cutting edge for a reasonable time when taking very heavy cuts at a previously unattainable speed, but also keeps its cutting edge when used with a moderate cut and speed for

a far longer period than was previously obtainable, its advantages, if applicable to complicated milling cutters, are clearly just as great as for the simpler tools taking the heavy cuts. For, although the nature of the work upon which the cut is taken, and the finish required from the cut, may not allow, in the case of the milling cutter, any great increase of speed or feed by the use of high-speed steel, and consequently little direct saving upon the time occupied in doing the work, as in the cases of the other classes of tools, yet an equally important saving is effected upon the cost of supply of the tools themselves. The milling cutter is the most expensive of all the tools used by engineers in cutting metals. In the simplest milling cutter the cost of workmanship so largely exceeds the cost of material that a moderate increase of life obtained by improvements in the raw material far outweighs a considerable increase in its original cost, provided that there is sufficient work in sight for the cutter to ensure its being fully employed for its maximum possible life. Perhaps it is this ruling condition which has led to somewhat less attention being paid to the application of these steels to milling cutters in general engineering workshops than to other cutting tools. For in these, with the exception of a few simple cutters generally useful for roughing out or for finishing simple profiles likely to recur, it has perhaps generally been more economical to make the cutters from ordinary qualities of tool steel, or even in some cases from case-hardened mild steel ; hence the preparation of an elaborate milling cutter from high-speed steel has not received quite the same general attention as the preparation of other cutting tools of maximum endurance.

The case, however, is different in a number of workshops where the interchangeable parts of many classes of apparatus and fittings depend very largely upon the use of formed milling cutters, and where the accuracy of the work so produced is directly dependent upon the accuracy with which the form of the cutter can be maintained for a prolonged period. It is desirable also that the cutters should have as long a life as possible in actual service, not only to minimise the first cost and upkeep, but also to keep the output of the machines as continuous as possible, by reason of

freedom from delays in changing the cutters. These points depend chiefly upon :—

- (1) The quality of steel from which they are made.
- (2) The method of hardening adopted.
- (3) The care and accuracy with which the new cutters are made.
- (4) The facility and correctness with which the cutters can be ground up when they have become dull or lost their accuracy.

(1) *The Steel used.*—There is, of course, nothing to compare with the recently developed high-speed steels as a material for cutters which are required to work at a high cutting speed and have the maximum possible life; and no difficulty is now experienced in obtaining work with a sufficiently satisfactory finish, provided care is exercised in the grinding and finish of the cutters, in the manner which will be described, and also if the cutting speeds and feeds are suitably arranged. Any of the best-known makes of this class of steel can be used in conjunction with the system to be described.

The blanks are annealed, packed in spent powdered charcoal and steel turnings in cast-iron pans with covers which are luted down. These are placed in the annealing furnace first thing in the morning, and are gradually heated up to 700° C. to 750° C. (1,292° F. to 1,382° F.); this heat is usually reached by 1 o'clock and is maintained until about 5 o'clock, when the dampers are closed and the furnace is allowed to cool gradually for forty-eight hours. It is found that some makes of high-speed steel are satisfactorily annealed by the makers, but it is not the universal practice. Annealing in this manner is found to give thoroughly satisfactory results.

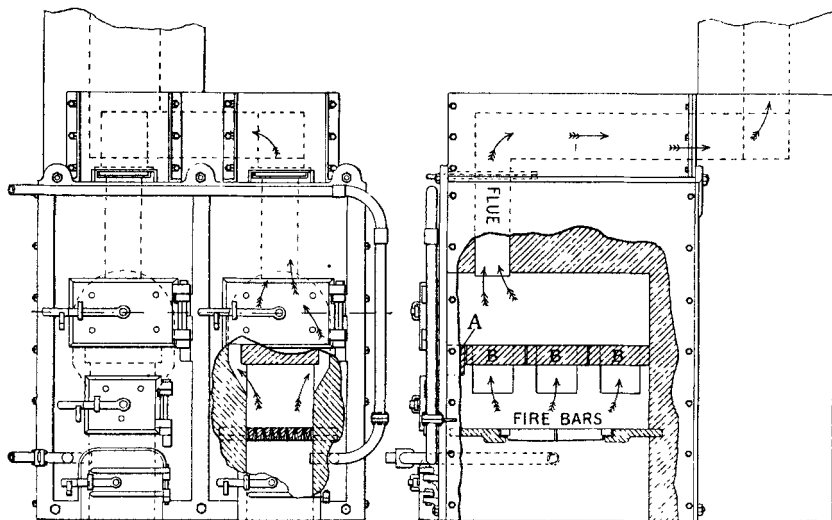
(2) *Method of Hardening.*—The furnace used for hardening cutters is shown in Fig. 1 (page 1024) and Fig. 2, Plate 83, and it has been found specially adapted for obtaining a soaking heat, together with the high temperature necessary in treating this class of steel, and freedom from oxidation. The furnace is coke fired and has a forced draught, and temperatures up to 2,300° F. can be obtained.

In using the furnace the cutters are packed closely in powdered charcoal in sheet steel boxes about 6 inches by 6 inches by 3 inches. These boxes take from 2½ to 3 hours to reach the necessary hardening temperature, the time taken varying with the weight of metal to be

FIG. 1.—*Hardening Furnace for Cutters of High-Speed Steel.*

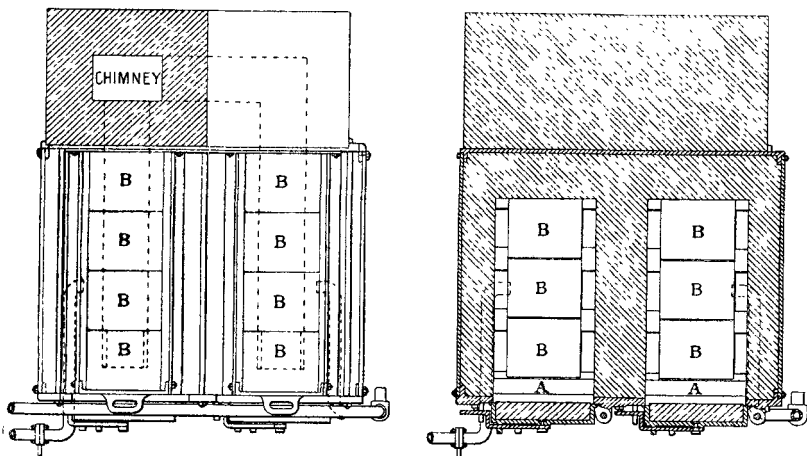
Front View.

Side View



Plan.

Transverse Section.



Inches 12 6 0 1 2 3 4 5 6 7 8 Feet

heated. The hardening temperature varies somewhat according to the class of steel being used, but may be said to be between 2,000° F. and 2,100° F. The exact temperature necessary for satisfactorily hardening any particular class of steel is previously determined in the laboratory by exact experiments, and the temperatures obtained in the furnace are checked by means of a Féry radiation pyrometer—also shown in Fig. 2, Plate 83. This pyrometer is itself tested against a standardized Callendar pyrometer, and has so far been found to give extremely reliable results.

The cutters when sufficiently heated are quickly removed from the charcoal in which they have been packed, and are at once placed upon the hardening table shown in Fig. 3. This table is of a type frequently used in workshops for heating tools by gas, but when used for hardening cutters, air only is supplied through the two nozzles. These can be moved as required about vertical pivots so as to cause the air-blast to impinge upon the periphery of the cutters at any required points and simultaneously upon the vanes of the spindle upon which the cutter is placed, causing the whole arrangement to rotate and thus equalising the cooling and hardening effect. The air delivered upon the cutter is drawn from an old culvert which passes under the floor of the workshop and through which a stream of water continually flows; hence at all times of the year a supply of cold damp air of maximum cooling effect is available. The temperatures used in hardening are such that the edges of the cutters are almost fused, and although different makes of steel have been found to vary somewhat in this respect, the general statement remains true of all of them. At the same time it is found that this fusing effect for a given heat is considerably minimised by the method of heating in closed boxes as compared with the ordinary method of heating tools, either in a muffle or in a direct gas-flame, and even the scaling, which, with the latter systems is frequently very marked, is, with the method now described, so slight that the cutters can be wholly freed from scale by placing momentarily under a revolving scratch brush.

All difficulties as regards the expansion of the hole through the cutters in hardening are met initially, leaving the bore slightly

smaller than is ultimately required—on the average about 0·01 inch less than the finished diameter; the expansion is usually about 0·003 inch to 0·005 inch, the average diameter of the mandril being 1 inch. After hardening, the milling cutters are first chucked truly with the outside diameter in a self-centring chuck, and the internal bore is ground up truly to the finished diameter. After this the hardened cutters are chucked upon mandrils and the teeth are finished upon the special machines to be described.

(3) *Forming Cutter-Teeth*.—Accuracy of form of the cutters is secured, both when being cut in the first place and also subsequently reformed, by turning the blanks and milling out the teeth in the ordinary manner, and then backing them off in the machine shown in Figs. 4 to 7, Plates 83 and 84. In this machine the cutter to be formed is carried on a dividing head, so that one tooth at a time can be presented to the small milling cutter *a*, Fig. 4. This is mounted upon the cutter spindle *b* driven by a pulley *c*, from which cat-gut cord runs through an overhead gear, allowing the spindle to be moved within the necessary limits. The small cutter spindle-frame forms part of a system of adjustable pantograph links, so that its movement is an exact reproduction in miniature of the movement of the tracing pin upon the former *d* fixed in front of the machine. The operator, by means of the handle *e*, moves the pin *f* lightly along the former, and consequently also moves the cutter over the tops of the teeth to a similar but smaller shape. The small cutter is enlarged in diameter towards one end, so that it cuts away the back of each tooth upon the cutter to the necessary extent. Commonly a conical backing-off cutter is used, the angle of the cone being 20° and the setting being such as to give an angle of relief of 10°, that is, the axis of the cone is at right angles to the radial face of the tooth being backed off. It will be seen that this characteristic enables the machine to produce teeth of any form, upon a cutter backed off in every direction from the cutting edge, so that a clean cut can be taken with the sides as well as with the tops of the teeth.

In the case of those milling cutters in which grinding back the faces of the teeth so backed off might cause serious inaccuracy, owing to its throwing back the radial cutting edges of the teeth, the

cutters are built up of annular sections which are either clutched together or clamped together upon plain faces, from which, after a particular grinding or series of grinding operations, the same amount is ground off as that by which the radial cutting edge has receded. Where the edges of the teeth are parallel or nearly parallel to the axis of the cutter, the profile is of course not appreciably affected by grinding back the faces of the teeth. A further means of avoiding such errors is also to be found in grinding the tops of the teeth in the manner subsequently described.

As it is found advantageous, in order to obtain a fine finish, to use helical teeth upon milling cutters, a fitting consisting of a sleeve with spiral slot—see Figs. 6 and 7—can be mounted on the same spindle as the milling cutter. A pin on a hinged arm centred above the backing-off cutter spindle is arranged to slide in the slot in this sleeve so that, as the frame carrying the copy and the cutter spindle is moved backwards and forwards along the axis of the cutter being backed off, the helical teeth are maintained in correct relation to the backing-off cutter; while at the same time they are backed off to the correct profile. Theoretically, of course, in such cases the axis of the cutter being operated upon could be inclined to the axis of the backing-off cutter spindle at an angle equal to that of the spiral of the cutter being produced, but in actual practice it is found that this adjustment is very seldom necessary, as the cone angle of the backing-off cutter, and also the amount of material which can be removed from the cutting edge of the cutter being produced, are both, comparatively speaking, small.

This machine has thus been found not only capable of backing off satisfactorily cutters of a shape which could not be backed off along the whole length of their profile in an ordinary relieving lathe in one operation, but it has been found possible to do the backing off in, approximately, one-third of the time required on a relieving lathe, while at the same time a less expensive class of labour may be employed, and the finish of the teeth is found to be better.

(4) *Grinding Cutters.*—Figs. 8 and 9, Plate 84, show the machine used for sharpening the cutting edges of the hardened milling cutters

and subsequently regrinding their faces or edges as required from time to time.

This machine has a grinding wheel mounted upon a spindle suspended on a swinging frame and follows the work by the use of a former, the profile of which is of the same magnitude as the one to be ground. In an ordinary way this former would not have the exact outline of the shape desired on the finished cutter, corrections having to be applied for the diameters of the tracing roller and also of the grinding wheel, the latter item being, of course, itself variable. This difficulty is overcome by using grinding wheels of special fast-cutting artificial stone, which will perform a considerable amount of useful work before being appreciably reduced in diameter, and by making the diameter of the tracing roller equal to the diameter of the grinding wheel; there is in addition of course an adjustment for raising or lowering the former.

The milling cutter being ground is, as before, mounted upon a dividing head in the case of straight cutters, or upon a dividing head provided with helical sleeve in addition in the case of helical teeth cutters, and all the teeth are first ground along the tops to profile and afterwards in the usual manner down their faces, the grinding wheel being, of course, set over to the angle of the spiral. The cutter thus finished has edges both of the maximum keenness and also of the maximum endurance due to correctly hardened high-speed steel, as only the thin skin partially oxidised in heating before hardening is removed.

Hitherto the apparatus employed upon sharpening profile cutters for milling machines in repetition work, such as is produced in small-arms factories and elsewhere, has required the handling and attention of men with considerable training and skill, liable to error and consequently well paid to avoid it. The provision of simple machines such as those described now enables an unskilled man to regrind correctly all cutters brought to him with considerable rapidity and the minimum possibility of error. By standardization of the pitches of the teeth of the cutters and their angles, and by the provision of suitable templates for each of the cutters commonly required, the use of these machines has been found to result in



distinct economy, both in the upkeep of cutters and also in the quality of the work turned out.

Considerable advantages result from being able to reform accurately the contour of the teeth in addition to grinding the face. In ordinary use the teeth of milling cutters are damaged not only on the face but to an even greater extent on the top, and it has frequently been found that removing, say, 0.002 inch from the top has as beneficial an effect as removing 0.006 inch from the face, and with this additional advantage that, when a tooth has been ground to its fullest extent from the face, it can be further sharpened on the top whilst still retaining its correct figure, until the tooth is too short through not allowing the necessary clearance; and this consideration will in many cases lengthen the life of a cutter by 10 per cent.

The life of some milling cutters prepared by the methods indicated above has been extraordinary; for example, a cutter working in a self-acting cross milling machine and operating upon the bodies of the service rifle at an average cutting speed of 69 feet per minute, with a feed of  $1\frac{3}{4}$  inches per minute and a depth of 0.08 inch, and taking a cut of an average width of  $1\frac{1}{8}$  inches and  $\frac{7}{8}$  inch long, has produced, at the time of writing, 39,170 bodies and is still good for about half as many more. This particular cutter has been reground across its face twenty-five times. The composition of the steel upon which it operates is 0.5 to 0.6 carbon with an ultimate tensile strength of not less than 35 tons per square inch.

The Paper is illustrated by Plates 83 and 84 and 1 Fig. in the letterpress.

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*Discussion.*

The PRESIDENT, in proposing a hearty vote of thanks to the author, said the subject was a most interesting one and of considerable importance.

Mr. GEORGE HUGHES said that he appreciated the Paper very much, and he believed it covered almost every point of difficulty in the manufacture of formed milling cutters. The introduction of the pantograph in the manner described was novel and ingenious. The first question he wished to ask was with regard to what the author considered a sufficiently satisfactory finish, but that question was practically answered, he believed, by the samples on the table. All those who had been associated with the use of high-speed steels for milling cutters knew very well that a great deal hinged upon what could be produced in the way of finish.

Another point not quite clear to his mind was what was meant by spent powdered charcoal. It was indicated in the Paper that the milling cutters were embedded in powdered charcoal for the purpose of annealing, and that appeared to be practically a system of case-hardening; although he had not done any case-hardening in connection with high-speed steels, he had found it most beneficial in connection with the ordinary carbon steels. The author stated (page 1025) that the air used for hardening cutters was drawn from a culvert, and consequently was always cold and damp. The practice at Horwich was, as far as possible, to get the air thoroughly dry. On the same page the author said that it was possible to remove the scale by means of a revolving scratch brush, but his experience had not been so good in that respect. As a matter of fact, he had practically abandoned air-hardening for milling cutters made of high-speed steel, and had adopted the process of oil-hardening, simply on account of the oxidation.

The question of finishing was again touched upon at page 1027, where it was stated that, in order to get a high finish, it was necessary to have helical teeth. He would be obliged if the author

would enlarge upon that point, because it was quite evident he had had vast experience in the use of high-speed steels, and any information that he could give, as to what he had found to be the most satisfactory in regard to the angles of the spirals, the pitch of the teeth, etc., would be much appreciated. He noticed that the author found a  $10^{\circ}$  backing suitable, and that he had standardized the pitches of the teeth and the angles of the helix.

He had a question regarding grinding wheels (page 1028), which was answered by the samples exhibited. It was well known that a successful grinding-wheel must not wear away too rapidly, and, at the same time, it must not fire the tool. The author had remarked that the high-speed steels had not given the success that might have been expected from the experience that had been gained with lathe and planer tools. That experience, he thought, was fairly universal, and it was supported by his experience at Horwich in the use of over 100 tools of different designs (samples of which are shown on Fig. 10, Plate 85), and manufactured from six or eight different kinds of material. The point that naturally struck one was why high-speed steels should not be so successful for milling cutters as for planer-tools, etc., and he did not think he could answer the query fully, but no doubt the author or some other member present would be able to do so. Was it on account of the design of the milling machine, or the design of the cutter, or the material itself? Was it due to the difficulty of getting the finish required upon the work upon which the tool was operating? It had been the practice at Horwich, before the introduction of high-speed steels, to demand that the cutter should not only rough out, but that it should finish as well, and that practice undoubtedly had saved time. With the introduction of the high-speed steel milling cutter, however, it would no doubt be advantageous to rough out with a high-speed, and finish with an ordinary carbon-cutter. He had a great idea that it was much cheaper to remove material in a lathe, or a planer, or a milling machine, than work it down by means of a steam-hammer in the forge. There was no doubt that the success of the lathe tool and the planer tool of high-speed steel was due to its property of "red hardness," or capacity for removing metal at a very high temperature. This

(Mr. George Hughes.)

property, however, could not be utilized in a milling cutter, as the teeth were not constantly cutting, but only intermittently shearing.

The author had touched very concisely on hardening, which was a most important matter in connection with high-speed steels. As he had already intimated, he had abandoned the air-hardening process for milling cutters simply on account of oxidation. Anyone who had worked in connection with hardening of a lathe tool would know that oxidation commenced immediately, and he would have seen that a scale was formed, and would have noticed the manner in which it flaked off. That was a very important point, and something was going on during the period of oxidation that he could not quite understand. It was known in connection with ordinary lathe tools of high-speed steel, that if they were not well ground after hardening they were not a success, and his experience had been that on occasions they were better after the second grinding, and sometimes even after the third grinding. It appeared that some molecular change was taking place immediately below the surface metal, and that either the chromium, wolfram, or vanadium, lost its capacity for controlling the structure. It was difficult to grind the face of the tool of a milling cutter to remove what might be termed (for want of a better description) "the soft surface."

He had noted with pleasure that the author spoke highly of the Féry pyrometer, as he was just installing one, together with a thread recorder, in connection with some annealing furnaces, and he hoped to get some considerable value from its use.

Mr. H. F. DONALDSON, Member of Council, thought it was a little unusual for a Paper to contain so much detail, in regard to what might be termed shop secrets, as the author had been able to set forth. For that reason he thought the Institution was to be congratulated, because there was a certain kink in the human mind which required that each individual should selfishly do the best he could for himself. If he had got a good thing he was apt to think that he had better keep it, rather than let others know it. But circumstances played into the hands of some people, and it so happened to the author and a few others who were servants of the

public. It was not only their pleasure but their duty to let the public know what was going on in the Government workshops, so that the strength of the country's trade might be increased.

The author had dealt with a whole series of difficulties, as Mr. Hughes had said, but of course there were various degrees of difficulties. It was hardly in order to tell a story, but he would ask the President's permission to do so. It happened a good many years ago, when rule of thumb, or perhaps rule of eye, was even more pronounced than it was now, that there was a certain hardening smith in a certain shop in the north who acquired the character of being absolutely certain in his manipulation of any difficult piece of hardening. He was watched, and was seen carefully to deposit something which he took out of a piece of paper carried in his pocket on every piece when hardening. He was very successful. A certain pupil apprentice was put to work with that man for some time, and they became very friendly. The apprentice was in the position to do the man a good turn, and certainly the man in question did the pupil apprentice several good turns. When the time came for the pupil to be out of his time, the workman said to him: "You have been a good pal to me; I wish you well, and shall always be glad to help you." The young fellow said to him: "Well, I have often watched you, and I wish you would tell me what you take out of that paper." "Well," the man replied, "if you will not tell anybody I will tell you—'taint nothing but a bit of chalk." The apprentice asked him what that had to do with the hardening, and he replied: "It has nothing to do with it, but if you look at the things which I harden you will see that I never enclose any steam in them when I dip them." By that means he was able to avoid a great deal of distortion; at any rate the result was that he hardened without distortion where other people distorted with great regularity. For that reason he had said there were various degrees of difficulties. There were now pyrometers which removed the necessity for the eye or for the pinch of chalk, but he did not think they had got to anything like the bottom of the difficulties which attached to the use of such things as high-speed steel. It had been, he thought, quite erroneously believed that because steel was called a high-speed steel,

(Mr. H. F. Donaldson.)

therefore it was to be expected to be unsuccessful with light finishing cuts at slower speeds. One of the things the author did in his Paper was to explode that idea, particularly in cases where the tools were expensive or where it was important to refrain from breaking into the continuity of an operation. There were many operations in the manufacture of ordnance where continuity of operations was of the greatest importance, and where heavy cuts were not of so great an importance, even where great speed of cutting was not of so great importance. In those cases of high-speed steel, particularly in such things as milling cutters running at high speeds or higher speeds than before, the length of life of the tool itself was of very great importance indeed, and for that reason the use of high-speed steel he thought had not received all the attention which it might receive.

There was a point in the Paper which was perhaps also a little astonishing, or likely to be a little astonishing to many people, namely, that the result of the investigations in practical working detailed by the author was that, with a cheaper quality of labour, a better quality of tool and a higher quality of finishing was obtained. It might seem almost paradoxical, but the fact remained that it was so, because there were brains in the idea and there had been brains in bringing the thing to the state of perfection which it had so far reached. He thought there were other places in the country where the application of more brains would redound to the credit of the trade and certainly to the pecuniary profits. He hoped that the example which the author had set of going into details would encourage gentlemen who were engaged not only in operations of milling but in other operations of the workshops, which he thought lent themselves very much to further investigation, to come forward and say something about them, because, though for the moment the individual might benefit, it was very much more important to the individual himself that the country and the trade of the country should be improved. For that reason he hoped that there might be a great deal more of shop secrets disclosed.

Mr. ARCHIBALD K. BRUCE said what struck him most in the Paper was the application of scientific methods in the production

of milling cutters. Too often the knowledge brought to bear on the preparation of these tools was entirely inadequate, and such a communication as the author's pointed unmistakably to the fact that the empirical *régime* in this connection was played out. It was of interest to note that the refinements dealt with in the Paper had been carried out in a small-arms factory, since, if his memory served him, it was the demand for rifles during the great Civil War in the United States which set in motion modern manufacturing methods. Many present would associate with this far-reaching development the name of Mr. Samuel Colt, of the Colt Fire Arms Co., who did so much for the advancement of the manufacturing methods which obtained universally today. Happily, the ingenuity of the author had not been exercised by such a contingency as an abnormal war demand for small arms, but it was noteworthy that the refinements hinged once more on the production of rifles.

The author said (page 1022): "The nature of the work upon which the cut is taken, and the finish required from the cut, may not allow, in the case of the milling cutter, any great increase of speed or feed by the use of high-speed steel"; but there was just another factor which, though it might not be of much importance in machining the component parts of a rifle, was of most profound importance in heavier work. That factor was the machine itself. Those who were familiar with heavy milling operations would appreciate the need for that rigidity which was only to be obtained by a combination of sound design and construction. In both British and American machine shops, milling machines were often rendered conspicuous by reason of excessively noisy working, and while much of this could be put down to loose gibs, bad management, incompetent operators, etc., the fault lay frequently in the machine not being stiff enough to stand up to the given work. This was a consideration which became of the first importance when milling with high-speed steels, and just as the design of planers and lathes had been revolutionized by the new steels, so also would the milling machine have to be modified before equivalent duty could be obtained. There were indications in various quarters that these requirements were receiving attention and though not exactly germane to the subject of the Paper, perhaps

(Mr. Archibald K. Bruce.)

the author would refer in his reply to the matter of machines. He noticed that the word "sharpening" was used rather than "grinding" in connection with the preparation of the working surfaces of milling cutters. People did not always differentiate between grinding and sharpening, but it was one thing to "grind" a cutter, and quite another thing to "sharpen" it. With regard to the figures given at the end of the Paper, he thought the results very striking, and manifestly any methods or material which lengthened the working life of milling cutters while maintaining uniformity of product could not be neglected. Referring to the pantographic apparatus, and the system of backing-off employed, he thought they were beautiful arrangements for the particular purpose, and there could be no doubt that a Paper of this kind was most valuable, dealing as it did with progress in the manufacture of a tool, which, like the milling cutter, was so intimately associated with the manufacturing efficiency of a manufacturing country.

Mr. GERVASE H. ROBERTS said that, having had the advantage and pleasure of discussing with the author the methods here described, he was not now in a position to make any destructive criticisms; those that he had to make were made to the author at the time. He might, however, here be allowed to express his own opinion, namely, that the process as carried out at Enfield was a very neat and ingenious one, and eminently adapted to the needs of Enfield productions. He referred more particularly to the paragraph on page 1022, where the author made the point that the use of formed cutters was particularly applicable to repetition work. It was well known that in ordinary engineering workshops, which had to turn out perhaps only one article of a kind from one set of patterns, there were many jobs in which it did not pay to make formed cutters, and the same thing frequently applied even where there were a score of things to be made; but where a large number of things had to be produced of exactly the same kind as in the manufacture of small-arms, bicycle components, sewing-machines, and the like, it distinctly did pay to make such cutters. He had had occasion to look into the question in some detail a little time



ago, and, dealing with cutters made of three typical kinds of steel, namely, (1) ordinary soft Bessemer or Siemens-Martin steel, (2) case-hardened crucible cast-steel, and (3) so-called high-speed steel, he found that, taking all things into consideration—the first cost of the steel, the cost of machining, machinery charges, and all the rest of the incidental costs—it was possible on certain classes of work to fix roughly three limits in respect of the amount of material to be removed at or below which the cutters described might be most economically used. He was not in a position to give exact figures; indeed such figures were only strictly correct for the particular work then under consideration, but roughly speaking those limits were in the proportion of 1, 2, and 3. That was to say, if there were only a certain amount of material to be removed, one could only afford to use case-hardened mild steel; if there were between twice and three times as much material to be removed, it would pay to use crucible cast-steel; whilst for the removal of a greater amount of material high-speed steel cutters were most economical. He was speaking of formed cutters only, not plain cutters.

On page 1027 the author gave the practical conclusions he had arrived at in respect of the Enfield method of manufacture of formed cutters, and he wished to emphasise those conclusions himself and give what he thought was another reason why the use of such a method must extend in the future, and that was the well-known fact that, in the case of milling cutters, the tendency today was all in the direction of coarsening the pitch of the teeth. Twenty years ago cutters had a pitch of tooth of  $\frac{3}{16}$  inch or thereabouts, but cutters were used today for removing much larger quantities of material which had a pitch of teeth of anything up to  $\frac{1}{2}$  inch, and the Enfield method to his mind was much more eminently adapted to the production of such cutters than the other method, namely, by the use of the backing-off lathe. He did not want to hurt the feelings of any of his friends engaged in the manufacture or sale of backing-off lathes, but he was bound to say that such backing-off lathes when at work, and especially so when engaged on small cutters, produced on anyone responsible for their maintenance and upkeep,

(Mr. Gervase H. Roberts.)

an expression not wholly pleasant. The operation was—if he might so put it—kinematically correct but kinetically unsound.

The author said (page 1023) it was found that some brands of high-speed steel were satisfactorily annealed by the makers, but it was not the universal practice. Speaking from an experience of some hundred tons of high-speed steel which had passed through his hands, he wished to emphasise that. It was eminently desirable that the manufacturer should anneal and thoroughly anneal such steel before it was sent out from the works, and he had seen many cases of steels not thoroughly annealed which had practically fallen to pieces before being received into stores. It was apparently a peculiarity of high-speed steel that it was very sensitive to molecular stresses, which were likely to be set up in the various processes of manufacture. Tilted or hammered rectangular sections did not seem to be so affected, but large rolled sections—especially when over 2 inches in diameter—were very liable to be damaged by such internal molecular stresses. A somewhat analogous condition was sometimes found when high-speed steels were nicked cold. They would not stand cold-nicking and were liable to split, or at any rate to start fine hair-cracks, which soon led to failure of the finished tools when put into service. He wished to emphasise what Mr. Donaldson had said, that the Paper was one of a class which would, he thought, be acceptable to the Institution, and, speaking as one of the members interested in more purely mechanical matters, he hoped they would have more Papers of the same type.

Mr. H. C. KING said the author enunciated some of the properties of high-speed steel (page 1021), and he would like just to interpose another property for which it had commended himself to him—the property of withstanding shocks, which was manifestly an advantage in connection with lathe-tools. In one of the locomotive shops of the Great Western Railway they had practically doubled the output of the group of crank-turning lathes. A tool that would very accurately take  $\frac{1}{4}$  inch off one side of the diameter and  $1\frac{1}{2}$  inches off the other side was appreciated. If the operator did dig in, the tool did not break, as it invariably did when made of ordinary carbon steel.

He could remember the day when to offer to introduce a milling tool into a shop was very closely allied to the old present of a white elephant. He recollected distinctly the distress of one works manager eighteen years ago, who found that the high-priced steel he had to buy, to satisfy the requirements of the economical tool, was going beyond all his expectations and his directors' estimates. He found the happy solution in seizing some old railway axles of about 0.35 per cent. carbon, and by forging them, and in the soft state shaping them easily and then case-hardening them, he realized a cutter which lifted him out of the whole of his difficulties. Fortunately these were happier times, but it was well to consider the difficulties which had to be contended with in the initial stages.

The author had grouped his observations under four heads (page 1023), and he would like, if he might, to refer to the question of hardening later on. The hardening furnace, which his firm used, he believed was a somewhat similar furnace to that mentioned by the author, but it possessed two chambers, the upper one being the cooler. Having soaked them above, they were put down below to encounter the higher heat. He would like to express an incredulity at the method of heating described, and he did so though he thought the previous speakers had been wholly laudatory. He ventured to submit that the use of the Féry radiation pyrometer was more pleasing than beneficial. The Callendar pyrometer was well known and valued, but even in that case it was necessary to apply correction for the mass of the steel. The Féry pyrometer, as far as he had met it—he had never had the privilege of using one in his own works—had never appealed to him. Its use, as far as he was aware, consisted in the facility with which one could stand out of the heat and determine accurately the heat within the furnace by focussing the instrument upon some part of it. But having bought a most expensive instrument, it was still necessary to supply the human agency and to estimate with more or less success, as the size of the pieces varied, the length of time to be allowed after the instrument showed that the furnace was at the desired temperature.

He did not wish his remarks to be misunderstood, because he appreciated very fully the kindness of the author in detailing his

(Mr. H. C. King.)

methods, but if he read the Paper aright it was said that, after the furnace had been raised to the suitable temperature to which it was desirable the contents of the boxes should reach, the boxes were inserted, and the boxes took from  $2\frac{3}{4}$  to 3 hours to reach the necessary hardening temperature (page 1023). If that were true for the relatively small-sized cutters which he believed the author would be called upon to deal with, that was his correction; but in the case of larger pieces and a mixed variety of pieces which would come into the way of a trade hardening shop—and usually in railway works also there was a variety of sizes—after having determined the heat of the furnace, it was necessary to find the correction for the mass. Therefore he was afraid the determination by laboratory experiments of the desirable temperature, if it could be obtained, was not a sure guide to what one was really doing.

He was very interested indeed to read the ingenious arrangement by which the air-blast which hardened the teeth also rotated the specimen, so that all parts were cooled alike (page 1025). Some four or five years ago the foreman of his toolshop, who was present that evening, devised a similar instrument, but he had a vertical spindle on both bearings and a cone below and a cone above which self-centred the cutter very quickly, and he used the cutter teeth themselves as the fans. Very high rates of speed and very good results attended the use of that tool. For the centring necessary to grind out the whole accurately after hardening, the magnetic chuck was used. He was glad to know that the methods which had obtained in his shop so closely related to the judgment and sound experience which obtained in Government factories.

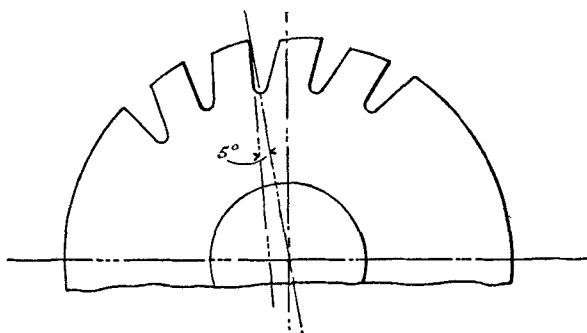
He would not have attempted to say so much that evening if it had not been that he feared some of the smaller users of steel might be prevented by the thought that they had to have a Féry pyrometer and special furnaces, in order to use high-speed steel cutters. His company's first experience with high-speed steel in the form of milling cutters was an astonishing success. The advantage of the use of high-speed steel was fully established then, with only a cotton-seed oil-tank, water-cooled, and a smith with a good eye, and was then as much appreciated as it was today. Raising the steel to a

temperature approximating to about  $950^{\circ}\text{C}$ . ( $1,742^{\circ}\text{F}$ .), and allowing it to fall to about  $600^{\circ}\text{C}$ . ( $1,112^{\circ}\text{F}$ .), which about approximated to a dull mahogany red, and quenching it in cotton-seed oil, gave the cutters of the most varied size an endurance on the milling machines of fully four or five times the amount of life they had ever been previously able to obtain.

Mr. FRANCIS CARNEGIE said, in view of the rapid application of high-speed steel in engineering workshops, he thought the members must be very grateful to the author for his most practical Paper. Four considerations were mentioned on page 1023 which combined to ensure the maximum life of a high-speed steel cutter, and he thought to those might be added the following:—

First, the teeth of the milling cutter must be correctly designed. To obtain the maximum cutting effect the tooth, besides being correctly relieved at the back, should have a rake of about  $5^{\circ}$  with a radial line passing from the centre of the cutter to the edge of the tooth, as shown on Fig. 11. The material operated on with cutters made as below was from 0.5 to 0.6 per cent. carbon steel.

FIG. 11.



Second, as to the number of teeth employed in a milling cutter. A figure milling cutter with a large number of teeth had a markedly shorter life than one with fewer but deeper teeth. Two cutters had been passed round of exactly the same form and diameter, one with

(Mr. Francis Carnegie.)

sixteen and the other with thirty-two teeth. The one with sixteen teeth of helical shape gave as good a finish as the cutter with thirty-two teeth; the cost of the former was 35 per cent. less than, and its life from three to five times that of the latter. Also, the sixteen-teeth cutter provided greater facilities for re-grinding a dull mill, and those who had seen it would readily recognize that by grinding the face of the tooth the contour of the cutter was not altered, whereas in the other the accuracy of the contour would be lost unless there was a special machine for re-grinding.

Third, with regard to the lubricant used in cutting the material upon which the mills operated, the works manager of a motor-car works said that he had been able to increase the life of his milling cutters from two to ten times, by using ingredients mixed with distilled water instead of the ordinary untreated water. He had no data to substantiate that statement, but repeated it for what it was worth. Condensed steam from an engine might serve the same purpose as distilled water. After carrying out numerous experiments with lubricants with high-speed milling cutters, his firm now used a special oil mixed with water in the proportion of 1 to 50, and that had given excellent results.

The author mentioned in the Paper a method of annealing (page 1023), which he understood referred to blanks. After a high-speed mill was worn out on a machining operation, an engineer could not afford to throw it on the scrap-heap owing to the high cost of its material. It was therefore necessary that such a mill should be re-annealed and reduced to one of a smaller size by re-forming. The method of annealing in the Paper, while giving excellent results for new milling cutters was hardly suitable for re-annealing worn-out ones, and his firm's practice with such cutters—a practice they had found very successful—was to put them in new charcoal in wrought-iron pans, hermetically sealed, then to place the pans in a furnace and heat to a temperature of from 1,500° to 1,900° F., according to the make of steel. Allow them to soak in the furnace at this temperature for one hour and a half, after which the furnace was cooled gradually, and the cutters were then removed; or, after the

one hour and a half's soaking, remove the wrought-iron pans from the furnace and bury in sifted ashes until cold.

Mr. WALTER CARTER said that the endurance urged in favour of high-speed steels for milling cutters was quite as valuable a feature of such steels when used as turning and planing tools, twist drills, etc. He would instance the use of high-speed steel for turning large forgings, gun-tubes, etc., where sometimes four and even six tools were cutting at one time. In such instances the costs of running the lathe and keeping the forging or gun in it was a serious item, greatly outweighing the cost of any tool steel. With ordinary carbon steels the tools would probably require to be re-ground every five or six hours. To stop work of the magnitude mentioned, even to change a tool, meant a loss of money; and if, as was now possible when using "A.W." high-speed steel, such a lathe as referred to could be kept working continuously for several days until the work was finished, a very great saving of time and money was effected from endurance alone, disregarding for the moment any savings resulting from increased cutting speeds and feeds.

With regard to milling cutters particularly, the use of high-speed steel for such tools was by no means novel or new, and he had been acquainted with the successful use of them for the last five years. The author referred to a very important point when he mentioned the quality of the steel from which the cutters were made. The quality of the steel used could not be too good. He (the speaker) ventured to suggest that in far too many cases the price of the steel received more attention than necessary, and had more bearing on the quality chosen than was advisable. Since the cost of the steel was usually but a very small item indeed compared with the cost of making the cutter, it did seem absurd to allow such a consideration to enter into the question, because after all, the better brand of steel would prove the more economical.

The annealing of high-speed steel was an important matter, as steel wrongly annealed would not give satisfactory results, and when in that state was frequently the cause of much difficulty and trouble. Correct annealing demanded the use of considerable technical

(Mr. Walter Carter.)

training and skill, together with suitable appliances, and should be done by the makers of the steel. Steels made by reputable firms were usually properly annealed and supplied in that state, this being still another advantage resulting from the use of high qualities of steel. He now learned that the annealing mentioned by the author (page 1023) referred to blanks. Was it also the author's practice to anneal the cutters before hardening with the object of releasing any strains that might have resulted from the machining operations, and by so doing minimising any tendency to subsequent distortion?

Referring to the method of hardening, that spoken of in the Paper appeared to be rather slow, and especially so if similar and successful results could be obtained by quicker and less involved methods. He thought such results were possible, and in support herewith submitted the hob of  $5\frac{1}{2}$  inches diameter and 6 inches long, made of "A.W." high-speed steel and hardened at the Openshaw works of his company in a muffle gas-furnace. The hob referred to had been heated to a temperature of about  $2,200^{\circ}$  F., and had been cooled by an air-blast. If this hob were inspected the surfaces would be seen to be smooth and free from pitting or scaling, and yet the steel was quite hard. Such and similar results were obtained daily by the same methods. The furnace used was shown on Fig. 12, Plate 86, the tempering tank on Fig. 13, and the hob on Fig. 14.

Regarding the method of hardening described by the author, he (the speaker) was not clear how the exact time was ascertained for withdrawing the boxes containing the cutters from the furnace. It had been mentioned that the higher the temperature the cutters were heated to, the greater would be their cutting efficiency. But the cutters should not be raised to a fusing heat, or if even so, fusing of the cutters must be prevented, for if fused the cutters would be spoilt owing to their forms having been destroyed. The heat should be something short of fusing. The fusing of the teeth of a cutter was not caused entirely by the effect of a high heat, but was the result of the cutter being maintained for a certain period of time at that high heat. This being so, he would ask by what means,



having regard to the cutters being in a sealed box, the temperature inside the box was arrived at and fusing prevented? A disadvantage, resulting from soaking the cutters at a high heat in the manner described, appeared to be that since the whole of the cutter was raised to that heat, a cutter so heated would be more brittle and less capable of withstanding shocks than a similar cutter where the teeth only were raised to the high heat. It was not to be inferred that he (the speaker) was suggesting that all cutters should be heated very rapidly, for such treatment would of course conduce to cracking, but there seemed to be such a wide difference between the methods described in the Paper and the methods he had known to be successful that the author's experience regarding the points raised would be welcome. It would also be interesting to know whether the author ever found the cutters to have "soft skins."

It was generally required that a milling cutter, when ground so much that it was no longer fit for use, should be capable of being annealed and re-cut. Cutters made of good quality steel would stand this treatment without showing any appreciable loss of efficiency, if hardened in some approved manner in the first and subsequent instances. He would be glad to know whether the prolonged heating mentioned in the Paper had any detrimental effect on the cutters in this respect, and also how it affected the cutter as regards distortion.

Referring to the question of "scaling," this defect was usually the result of the presence of an excess quantity of air in the hardening furnace. If the furnace were of suitable design and fitted with correctly proportioned gas-and air-supply pipes, any scaling would be of a minimum amount, whereas if air were present in excessive quantities, the cutter was in effect alternately heated and cooled, so that excessive and undesirable scaling resulted, and in some instances the cutters were even ruined.

In connection with the cooling of cutters, the author referred to a supply of cold damp air of maximum cooling effect being available. Since most makers of high-speed steel usually warned users against allowing such steel to come into contact with water or dampness it would be interesting to know what was the pressure

(Mr. Walter Carter.)

and temperature of the air used? If Dr. Ashton had any information comparing the use of damp air as against the use of dry air, he (the speaker) would be interested to know of the results. The author had refrained from any reference to cooling or quenching high-speed cutters in oil. Doubtless he had used such methods; if so, had he any figures bearing on the relative efficiency of cutters cooled by air-blast compared with the efficiency of cutters cooled in oil, both as regards their cutting powers and percentages of breakages? Having spoken of heating and cooling he might suggest that sometimes perhaps too much attention was given to the cooling, compared with the heating of the steel. In order to obtain the best results from high-speed steel it was essential that the manner and degree of heating should be correct. That being accomplished, the cooling, although important, was of secondary consideration. If the heating were improper, no matter how the cooling might be effected, the best results could not be obtained.

With reference to the working of the cutters, it had been mentioned that milling cutters made of high-speed steel were not relatively as successful as other and more simple forms of cutting-tools made of high-speed steel, also that such cutters were not very successful when used for cutting hard materials. With these conclusions he could not agree and would respectfully beg to differ. He could adduce numerous instances to the contrary, but perhaps a few would suffice. At the works of Messrs. Armstrong, Whitworth and Co. at Manchester, they were using "A.W." high-speed cutters daily, cutting nickel-chrome steel armour-plate at a cutting speed of 75 feet per minute. This steel of course was very tough indeed and difficult to cut. The depth of cut was  $3\frac{1}{4}$  inches and the width  $2\frac{5}{8}$  inches, the feed being 16 inches per hour, Fig. 16, Plate 86. In another instance forged steel had been milled at 180 feet per minute cutting speed, the depth of cut being  $\frac{1}{2}$  inch and the width  $7\frac{1}{2}$  inches. A feed of 6 inches per minute was obtained and 383 lbs. of metal were removed per hour. The skin of cast-iron had been cut at 75 feet per minute, the cut being  $\frac{5}{32}$  inch deep, and an area of 82.5 square inches was machined per minute. Cutting tool steel, a  $2\frac{1}{2}$ -inch "A.W." angle cutter,  $\frac{3}{4}$ -inch face 12 by 53 degrees, cut for

10½ hours without sharpening at speeds of from 62 to 113 feet per minute, the depth of cut being  $\frac{5}{16}$  inch and the feed per minute  $2\frac{1}{4}$  to  $4\frac{1}{8}$  inches. As showing the much greater endurance of high-speed steel over ordinary steel, he had with him a worn-out gear-cutter, Fig. 15, Plate 86, which had only been hardened in a smith's fire, but which had actually outlasted five ordinary American-made cutters, the high-speed cutter having cut 100,000 teeth against an average of 20,000 only by the ordinary cutters mentioned. The cutters were used under exactly similar conditions for cutting cast-iron gears of 10 D.P. for textile machinery, the high-speed cutter being sharpened after cutting 600 teeth and the American cutter after cutting 300 teeth. It could also be shown that cutters of "A.W." high-speed steel would outlast ordinary cutters when cutting hard steel castings. Cutting cast-steel motor-gears of  $2\frac{1}{2}$  inches pitch and containing 0.5 per cent. carbon at a cutting speed of 57 feet per minute, and a feed of  $3\frac{5}{8}$  inches per minute the cutter worked for three days without sharpening, whereas an ordinary cutter, cutting at 27 feet per minute and feeding  $1\frac{3}{8}$  inches per minute, required sharpening after working for  $3\frac{1}{2}$  hours only. It should be noted that in this instance the high-speed cutter not only worked at a higher cutting speed, but was also worked with a much greater feed per revolution than the ordinary cutter, showing the high-speed cutter to be stronger than the ordinary cutter and capable of withstanding the greater stress due to the heavier feed.

With regard to the finish obtainable from high-speed cutters, he had found that the degree of finish depended to a very large extent, in fact almost entirely, upon the speed and feed at which the cutters were worked. This was assuming of course the machine and details were in good condition. Certainly the finish of the samples exhibited by the author was most excellent, and reflected great credit on those concerned, but in order to judge of what was possible commercially the rate of work should always be borne in mind.

As to the number and angle of the teeth of the cutters, his own experience was that suitable standards would be very difficult to establish, for cutters that gave every satisfaction on a particular machine or operation did not always work equally satisfactorily under

(Mr. Walter Carter.)

changed conditions. Cutters with helical teeth have been found to produce a higher finish than cutters with straight teeth. But why? Would not a cutter with an infinite number of straight teeth produce work of equal merit? Such a cutter of course would be too difficult to make and also too expensive to maintain, so that cutters with helical teeth of a greater pitch were used instead. From this result, then, it might be inferred, and it was the speaker's experience, that the degree of spiral must be considered relatively to the pitch of the teeth, and further, the number of teeth in the cutter should be determined with regard to the form and size of the cutter, and if possible, with regard also to the machine it was proposed to use the cutter in, and the class of work to be done. Modern practice called for cutters with fewer teeth than formerly were considered desirable, but unless cutters so made had teeth of a correspondingly suitable spiral the results were scarcely satisfactory.

In the grinding of cutters, the author stated (page 1029) that considerable advantages resulted from being able to reform accurately the contour of the teeth, in addition to grinding the face. This would be so, and an advantage of great value. The author further stated that it had frequently been found as beneficial by only removing 0.002 inch from the top as 0.006 inch from the face. This would appear to lengthen the life of the cutter very considerably, say approximately in the ratio of 3 to 1, whereas it was stated that the lengthened life of the cutter was only 10 per cent. This was possibly a slight error, but it would be of interest if the author would kindly refer to it so that the actual increase of life of the cutter might be noted.

For the statements of results and the illustrations the speaker was indebted to the kindness of Mr. J. M. Gledhill.\*

Mr. B. J. HALE said the Paper was very interesting to him because he was daily occupied with milling cutters, and for some

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\* For fuller information on "The Practical Use and Economy of High-Speed Tool Steel" see Mr. Gledhill's Paper, read before the Glasgow and West of Scotland Foremen Engineers' and Ironworkers' Association, 11 November 1905.

time past he had been using similar machines for the manufacture of small profile milling cutters, the ordinary milling machine and grinding machine being used for larger cutters. With reference to the re-cutting of cutters, high-speed steel when brought to such a tremendous heat expanded and when the cutter required recutting, naturally when it was hardened again it would also expand, and that called for further expense in the shape of new mandrils for carrying the cutters. It struck him there might be another way out of the difficulty. Instead of having a plain parallel hole, the hole might be conical and the mandril might also be coned, and so take up any imperfections that might be due to the rehardening. A good rule for high-speed milling cutters was to keep the cutter as small as possible, and so to do away with the recutting where possible.

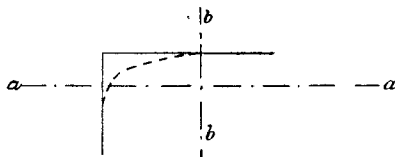
With regard to the annealing process, his firm had found the use of coal-dust very beneficial. They used ordinary coal-dust mixed with sawdust to the consistency of about 2 of coal to 1 of sawdust. The mixture was put into the box, covering the cutter well over, and the whole thing was heated up to about 900° C. (1,652° F.), and allowed to remain for one hour under that condition, and then the dampers were put down and the box allowed to cool in the furnace. Under those conditions they had always found their high-speed steel had come out wonderfully soft; in fact, they had been able to cut it much easier than carbon steels, and had no difficulty at all in milling high-speed steel at 54 and 55 feet a minute. The hardening was a matter of great importance, and he believed engineers would come to the conclusion later on that it was a matter of getting the correct heating, and that the tempering was a secondary consideration. As Mr. King had said (page 1041), wonderful results had been obtained in the early days by quenching in cotton-seed oil. He knew of one special machine which cut 100 outside cranks without regrinding.

Mr. MICHAEL LONGBRIDGE, Member of Council, regretted he knew too little to discuss the subject of tempering and hardening. The increase in the pitch of the teeth of milling cutters seemed to him mechanically sound, and he thought adoption of helical teeth was a

(Mr. Michael Longridge.)

natural consequence, because, by inclining the edges of the teeth to the axis of the cutter, it was possible to bring any tooth into action before the previous tooth had ceased to cut and thus to preserve a continuous contact between the cutter and the work, which would prevent shock and vibration and conduce to the production of a well-finished surface.

FIG. 17.



He had understood (or misunderstood) one of the speakers to ask why it was as beneficial to remove 0.002 inch from the top as 0.006 inch from the face. The reason seemed to be that the tooth of the cutter were somewhat as shown by the dotted line, Fig. 17, and therefore the sharp edge would be obtained by grinding down to the line *aa* on the top or to *bb* on the face.

The PRESIDENT said he had had a good deal to do with milling cutters himself, and would have pleasure in sending some further remarks on the Paper (page 1063), but there were one or two points he would like to touch upon, perhaps in the interest more of his younger friends than the older ones. It was pointed out by one of the speakers that to deal with old cutters for rehardening purposes, it was necessary to put them into fresh carbon. That seemed a very rational conclusion to come to, because all that was necessary to do really was to recarbonise the surfaces of the steel. Of course it was much more easily done with fresh carbon, which could be in a measure volatilised and so soak into the surfaces of the steel, than with old and partially consumed substances. Mr. Donaldson had mentioned the old-fashioned method of covering steel articles for hardening with chalk. After all, that was simply covering the surface with a good non-conductor, the idea being to bring the heat

gently into the heart of the metal rather than rapidly to increase the temperature of the surface without soaking into the heart. It was very much on the lines of the old oven for baking bread. To bake bread properly the oven must not be too hot because the temperature must soak through the whole mass to make good bread, and it was exactly the same, he thought, with any of the substances under discussion: the temperature must be regulated to the requirements of each case. That, he submitted, was the reason that the slow processes of heating were essential to good work in the tempering of cutters.

Another point raised was that of backing-off the teeth. With all due respect to his friend, Mr. Carnegie, who gave a diagram of the exact angle to cut the tooth (page 1041), he submitted that the angle at which the tooth must be backed-off very largely depended upon the consistency of the material that was going to be cut. This he had proved by experiment many times. It was the old tale. To cut soft metal it was necessary to use a very long sharp-tooth file, and to cut hard material to use a smooth cut file. In proportion to the hardness of the metal so was it necessary to decrease the angle and gradually work down to the material to be dealt with.

With regard to the value of a rougher pitch tooth, he submitted that in the question of the use of high-speed steel it was necessary to get rid of the abraded portions much more rapidly, and necessary, whilst driving the teeth at such a much greater velocity and bringing them so much more frequently and rapidly into contact with the surface to be cut, that they should be able to get rid of the debris which they were making without clogging the tool. That, he was also satisfied from experiments, was largely the reason why the rougher pitch cutter was a better one.

Mr. Longridge had called attention to the question of the intermittent teeth, and in that connection his story repeated itself. With a wood plane a much sweeter cut could be obtained with a bevelled plane iron, and the same applied to cutting mills. The tooth should be always in contact with the surface acted upon, and thus one came back to the old bevelled knife plane which was kept constantly going by being steadily kept in contact with the work

(The President.)

during the whole stroke of the arm. He would have the pleasure of sending to the Institution the results of a good many experiments he had been carrying out for some years on high-speed steel. There were several little peculiarities he had discovered, and amongst them was one that might be treated as a small joke. He would not mention the name of the steel, but it was a celebrated hard steel and was brought to him and used with great success. The manufacturers were extolling their steel as being so much better than anybody else's. He told them, "I do not know that your steel is much better than others I have got in the shop; I will drill a hole through it." A hole was drilled through the hard steel by a soft drill, and the secret was that the lubrication was made with turps. The hole was made, much to the horror of the gentleman who came to laugh and went away very grave, taking a piece of the steel with him. It took the firm some time to make out how it was that their hard steel had been drilled through, because they considered it was the hardest steel in the world at that time.

Dr. ASHTON, in reply, said that Mr. Donaldson and other speakers had referred to the divulging of shop secrets and the necessity of brains in the workshop. He wished to state that the Paper was presented by him not as his own work but because he was the head of the department in which the work was done, with his co-operation. Any improvements which had been made had been chiefly brought about by the zeal and intelligence of the management and foremen, by whom generally the processes had been worked out. He was glad to say that nearly all his assistants closely interested in the matter were present that evening to hear what the members had to say on the subject. He had endeavoured to point out the keynote of the Paper in the introduction, but it seemed to have been missed by some of the speakers: briefly it was the question of obtaining a fine finish from high-speed steel cutters. Some competitors in the manufacture of rifles would go so far as to say that it was impossible to get a fine finish with high-speed steel milling cutters. He had hoped that Mr. Driver of the Birmingham Small Arms Co. might be present, because he believed that when he was last at Enfield he was more or less converted.



Mr. Hughes had referred to the spent powdered charcoal (page 1030). Spent powdered charcoal was charcoal which had been previously used for carbonising, and had probably had its carbonising virtues to some extent taken from it, but which still contained a large proportion of silicious matter. Other speakers had supported that practice by saying that they used charcoal for annealing purposes, and Mr. Hale stated that he used coal and sawdust (page 1049). The main object of the charcoal under the circumstances in which it was used was not that of a carbonising material, although if it did carbonise the surface no particular harm was done, as the probability was, if it carbonised it, it was to such a slight depth that the thin section was taken off in the grinding operations. Its main virtue was to give a non-oxidising atmosphere during the heating, and being also comparatively speaking a non-conductor it gave a very uniform slow heating.

The use of damp air had been referred to. At Enfield that was regarded as an advantage, and he himself thought it was. They had also used oil cooling experimentally. Probably damp air gave a more rapid cooling than dry air, and it had the advantage that it was more nearly of uniform temperature all the year round. With a more rapid cooling in air there was less oxidation and less scale to knock off.

Mr. Hughes raised questions as to the proportions of the teeth, and the same thing had been touched upon by other speakers. Mr. Carnegie dealt with the rake of the face, which he took as uniform, and the President had taken exception to his stating that it should be uniform. At Enfield they were using a fairly uniform class of material, roughly speaking, steels varying in carbon from about 0.4 to 0.6 per cent. Therefore, for the sake of simplicity, a uniform rake and backing-off angle was, he thought, allowable. Mr. Hughes had referred to the helical angle of the cutters. The practice was to make that one turn of the spiral in 30 diameters of the mean diameter of the cutter, usually about 2 inches. The former used on the machine had its slot cut in a spiral of one turn in 60 inches, and for convenience was used for cutters of varying diameters.

Several speakers had referred to the length of life of cutters, and Mr. King had stated as his experience (page 1041) that the cutters

(Dr. Ashton.)

lasted about five to one in actual endurance of the cutting edges. His own experience was approximately the same. Some cutters of rather a different type had shown a longer life than others. Some punches and dies were made of high-speed steel of about 0·6 per cent. carbon for punching a thin sheet steel, and one tool had already punched out two million blanks where formerly only two hundred thousand were punched, and was still running, having been ground down without having broken.

With regard to the power of the machine referred to by Mr. Bruce (page 1035), the cuts at Enfield were very light for the most part, and though a high finish was required, sufficient stability of the machines was comparatively easily reached, although there were cases where, owing to the small size of the holes which had to be milled internally—he referred particularly to the sample of the trigger-guard placed on the table—the diameter of the cutter had to be small and the overhang of the cutter from the spindle had to be considerable. There had been some difficulty in such cases, and attention had been required in the design of the machine to obtain adequate stability. Mr. Roberts had referred to the proportion of the cost of the material to the cost of the tool (page 1037). In some cutters he was recently dealing with, he noticed that the cost ran through several sizes in approximately the same proportion, the cost of the cutter being about three times the cost of the material, which was a high-speed steel of first-class quality.

Several speakers referred to the annealing of the steel. With regard to the Féry pyrometer, he was afraid the Paper had rather misled Mr. King. The temperatures stated were checked by means of the Féry pyrometer. If he had not had the pyrometers, he would not have been able to give the members the temperatures that were being used, but having them he was able to translate into precise figures what was the practice before the pyrometers were adopted, the method having been worked out before they were adopted. The pyrometers thus formed a useful check, and had been indispensable, while preparing the Paper, in giving exact temperatures. They also assisted the management in checking the eye. He had not the slightest doubt that the foreman of the hardening shop was the

more certain of his own adequacy to give the uniform temperatures required, because every time he had been checked against the pyrometer he had been found as accurate as that instrument. But one of these days, there might be other men in charge of the shop who might not be so accurate as the pyrometer, and therefore he was glad to have that as a means of check.

It was rather interesting to note that Swindon in several respects had come very close to the methods mentioned in the Paper, for instance, with regard to the rotation of the cutter. The Paper was based on what was done at Enfield, and they had comparatively little knowledge of what others were doing, except in a few instances, where he thought they were doing a little better than other people. He was glad to find others had been working on the same lines. Mr. Carter had objected to the heating being carried to the point of showing a superficial fusing of the cutter. His experience, however, was quite different—that the work which was got out of the cutter thus heated was better. The cutter would last longer if the heat to which it was raised before hardening were such that the surface just began to run; it must not run much, but just show signs of running. With regard to ascertaining when those temperatures were reached in the boxes, that was a question of supervision of the furnace. The object of using the non-oxidising non-conducting packing surrounding the cutters in the boxes was in order that the temperature of the cutter should not vary rapidly. There was a considerable margin of time allowed for error without risk. Supposing in the hardening shop it were noticed that the furnace had had a certain temperature for a given time, owing to the fact that the cutter was surrounded with a comparatively non-conducting material, it would be known that that cutter must be at the same temperature today, within very small limits, as a similar cutter was on the previous day when the furnace had the same appearance gauged by the eye or by the pyrometer.

With regard to the durability of the cutters of high-speed steel under heavy shocks, that was outside his experience, and he did not propose to lay down any laws for such cutters under conditions other than those to which he had referred in the Paper. The

(Dr. Ashton.)

distortion in re-annealing and re-hardening cutters made it necessary to employ mandrils 0.003 to 0.005 per inch diameter larger than those originally used. He agreed that the heating was far more an essential matter than the method of cooling.

With regard to Mr. Roberts' remarks as to the pitch of teeth, the advantage of the high-speed steel cutter was that it could be run at a higher speed, and therefore maintain a good finish, so that a cheaper form of tooth could be used, which gave also the advantages the President referred to. The speeds were only given in one case, 69 feet, but he found in practice they ran up to about 114 feet for light cuts and high finish. With 114 feet per minute it was possible to use a more coarsely pitched cutter with all the advantages the various speakers had referred to.

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#### *Communications.*

MR. GEORGE W. GOODCHILD wrote that, whilst the practice of hardening high-speed cutters as described in the Paper was undoubtedly a very satisfactory one, yet it took much too long to harden cutters to answer the purpose of people concerned in the manufacture of milling cutters for the trade. His firm (Messrs. L. Loewe and Co.) had adopted throughout their Berlin works the hardening process by means of electrically-heated salt baths, Fig. 18, and had succeeded in reducing the time from  $2\frac{3}{4}$ -3 hours to about half-an-hour, which included the time for pre-heating which took of course most of the time, the bringing of the cutters up to about 400° C. (752° F.) occupying the longest time. It took only about a minute to bring the average cutter from 400° C. to from 750° to 800° C. (1,472° F.), and then another minute from there to 1,300° C. (2,372° F.), which they considered the right hardening temperature. The time stated above referred to heavy milling cutters, whereas it only took from 6 to 10 minutes to bring a small milling cutter to the right temperature.

Another great advantage of the electrically-heated salt bath was the total absence of any scale on the cutter, thus reducing the amount to be ground off for sharpening to a minimum, besides preventing the cutters from being distorted. Cutters thus treated retained their bright appearance, so that it was sometimes difficult to tell from the outer appearance whether they had actually been hardened or not.

The method of cooling cutters was also open to criticism. They found several years ago when they cooled their high-speed

FIG. 18.

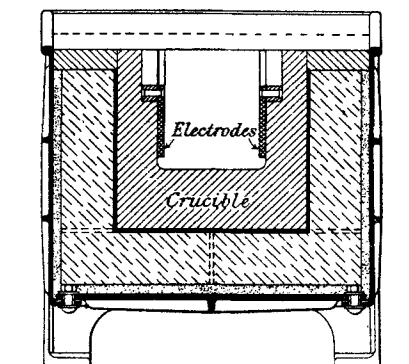
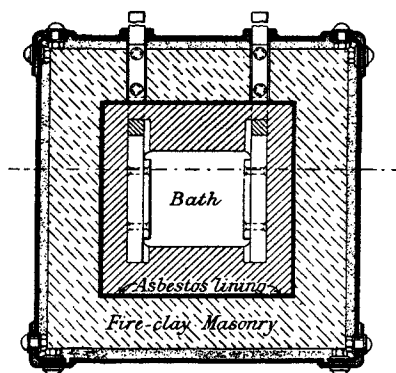
*Electrical Furnace with Barium-Salt Bath liquid at High Temperatures.*

The temperature in the furnace is in direct proportion to the consumption of electric energy. The cutters are placed in a tray and lowered into the bath.

Horizontal.

Sections.

Vertical.



tools in air-blast, that any moisture coming into contact with the hot tool tended to crack it, so that it became necessary to dry the air before it got to the nozzles. It was absolutely impossible to cool a cutter having a very heavy body and fine teeth in the air-blast, as the heat from the large central portion was not extracted fast enough, and thus did not permit a sufficiently rapid cooling of the teeth to harden them properly. With heavy cutters thus cooled the teeth were found to be quite soft, and for this reason they had adopted

(Mr. George W. Goodchild.)

the method of quenching the cutters from  $1,300^{\circ}$  C. to  $600^{\circ}$  C. ( $2,372^{\circ}$  F. to  $1,112^{\circ}$  F.), which was also being done in electrically-heated salt or metal baths. After this the cutters were allowed to cool down slowly in the air, and the whole process had the advantages of being cheap and absolutely reliable, besides effecting a large saving in time. A cutter of, say, 8 inches or 10 inches in diameter and 2 inches to 3 inches thick, having any kind of teeth, either on the sides or on the periphery, could not possibly be hardened in the way described by the author, whereas by their process absolutely reliable results were obtained.

The method of producing formed cutters by milling the form of the teeth with the aid of a small milling cutter, a template, and a pantograph arrangement was not new, and had been used by the Pratt and Whitney Co., of Hartford, Conn., U.S.A., some thirty or more years ago,\* but had long since been abandoned by manufacturers of milling cutters. The arrangement described for grinding backed-off cutters was more or less generally used before the invention of the machine-relieved cutter to produce cutters for cycloidal gear-teeth, but it was soon discarded owing to the disadvantage of having to anneal the cutter and re-cut and re-harden it each time it became blunt, as it was found that when grinding, instead of annealing and re-hardening, was resorted to, the emery wheels wore so fast that the resulting cutter was worthless for practical purposes. It was also found quite impossible to compensate for the wear of the wheel in a manner to give a result which would be accurate enough for ordinary cut machine gearing. If therefore such unfavourable experience were gained with the small shapes required for dealing with cycloidal gears, what chance would the emery or any other wheel have when grinding the face of a formed cutter 6 inches long, and having, say, twenty-four teeth? When the wheel had once gone round the cutter it had travelled 12 feet, and every experienced mechanic knew that when a small emery or other wheel had travelled 12 feet on the edge of a cutter of hardened high-speed steel it must be considerably

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\* See "Modern Machine-Shop Practice," by Joshua Rose, Second Edition, Vol. I, page 37.

reduced in size, which would appreciably affect the accuracy of the cutter.

From the above it would be seen that it was practically impossible to compensate for the reduction of diameter of the grinding wheel in a manner to give results which would be of any value, especially where accurate work to gauge was being undertaken. This method of grinding formed cutters was again employed a few years ago by a German engineer, but it was shortly afterwards abandoned, owing no doubt to the inaccurate results obtained. It was scarcely conceivable how an accurate milling cutter, say, for cutting gears, could be commercially manufactured or ground in the way described by the author.

In manufacturing a milling cutter it was necessary to remove a certain amount of stock, and when comparing the cat-gut cord-driven pantograph milling machine to a strong backing-off lathe with a 4-inch to 5-inch belt, and the massive tool on the backing-off lathe to the small milling cutter on the author's machine, it was evident that the backing-off lathe was better suited for rapid heavy work than the other machine. The small milling tool would not retain its proper shape and diameter for even finishing one milling cutter, and consequently the result would be a milling cutter of uneven dimensions; whereas, should the tool on the backing-off lathe not be accurate in the first instance—which was not very likely to happen—then this inaccuracy would be evenly found on the finished milling cutter, and as the same amount of error would appear on every single tooth and in the same direction it would be easy to make the correction.

His firm were using the pantograph in their works for shaping the forming tool, and after the backing-off lathe was once started, it would finish the complete milling cutter without any further attendance, whereas the machine described by the author required more or less permanent attention. Although the backing-off lathe had been described by one of the speakers as a kinetic incongruity, yet it was being used by all concerns interested in the manufacture of milling cutters for the trade. He regretted very much that his personal opinion and the experience he had gained did not coincide with the author's experience.

Mr. L. A. LEGROS wrote that he had for over three years been using milling cutters of high-speed steels in the production of automobile parts, and the results obtained in accuracy and finish of surface had been entirely satisfactory. In many cases where very hard and tough nickel- or chrome-vanadium steels required to be worked, this could be readily effected by cutters of high-speed steel when the ordinary tool-steel cutter failed.

The writer examined the cutters exhibited by the author and found the appearance of those which had been hardened but not ground to be identical with that which he had found best for bar cutters and turning tools. The edges showed slight fusing. This was just visible on the full sized photograph of the specimen exhibited by the author, *see* Fig. 27, Plate 86.

The cutters exhibited showed very clearly the advantage of backing-off by grinding, and the writer hoped that this system might be adopted by the makers of high-speed cutters in this country. Although good results could be obtained with the cutters ordinarily procurable, where the limits of tolerance were not very fine, as in automobile parts, it would be necessary to obtain better finished cutters for parts of small-arms or type-casting machinery, in which a high degree of accuracy was required. Most of the cutters exhibited by the author were unsymmetrical and could be readily sharpened on the tops of their teeth on the grinding machine adopted by the author. In the case of gear cutters, however, the corners forming the root of the tooth first became dull, and, owing to the fact that the sides of the cutter were usually nearly parallel at this part, it was necessary that the face should be ground before the cutter had suffered damage by rubbing; the maxim "keep sharp," which was stamped on certain well-known cutters, was even more applicable to the high-speed steel gear cutter.

The writer had used high-speed steel milling cutters also with considerable success for the several operations shown in the Figures herewith. The cutter shown in Fig. 19 (page 1061) had been used for producing castellated shafts from bars  $1\frac{1}{8}$  inches diameter (depth of cut  $\frac{1}{8}$  inch). The cutter was  $3\frac{5}{8}$  inches diameter and had 10 teeth. After cutting 130 shafts of a mean length of 6 inches (18 inches of



cut each), in 5 per cent. nickel steel this cutter had had  $\frac{1}{4}$  inch ground off the faces of the teeth. A second cutter of the same high-speed steel used for the same work showed a practically identical amount

FIG. 19.

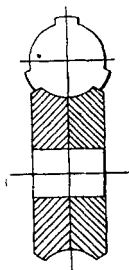


FIG. 20.

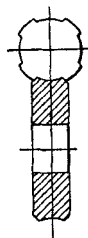


FIG. 21.

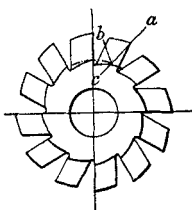


FIG. 22.

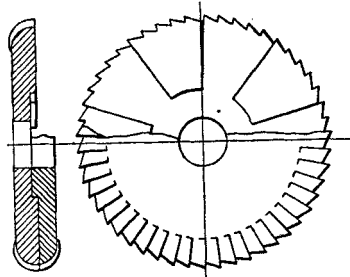


FIG. 23.

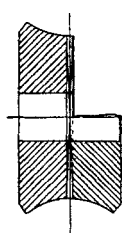
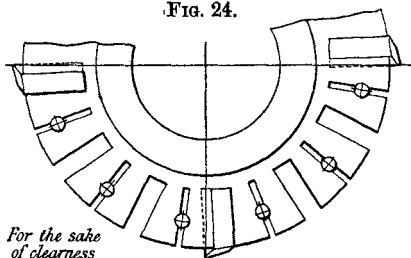


FIG. 24.



*For the sake  
of clearness  
only 3 teeth  
are shown*

FIG. 26.

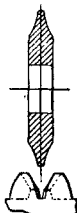
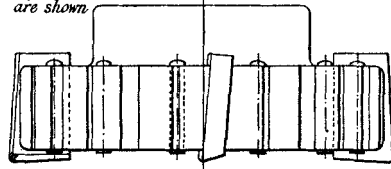


FIG. 25.



0 3 6 9 Inches

of loss for the same work. A similar cutter, Fig. 20, 3 inches diameter with 16 teeth cutting four castellations on a shaft  $1\frac{1}{4}$  inches diameter (depth of cut  $\frac{3}{32}$  inch), showed a loss of only  $\frac{3}{32}$  inch after

(Mr. L. A. Legros.)

cutting 260 shafts of 5 per cent. nickel of a length of castellation amounting to  $3\frac{1}{2}$  inches per shaft (14 inches of cut each). The limit of error in the above cases was  $\pm \frac{2}{1000}$  inch.

In the case of former cutters for gear teeth or other work in which high accuracy was necessary, the cutters should have radial faces, so that they could be properly tested with the gauges and maintained to standard. The suggestion made by Mr. Francis Carnegie (page 1041), that the face of the tooth should be inclined at  $5^\circ$  to the radius, led to trouble in practice with former cutters for two reasons. First, the shape was affected, since the cutting depth was lengthened, owing to the backing-off being of spiral form, *see* Fig. 21; the projected depth is proportional to  $a b$ , but the actual cutting depth is increased proportionally to  $a c$ ; in the case of a gear-cutter the curve became distorted, a matter of importance when silence of the gears was in question; and secondly, because the ordinary cutter-grinder produced a plane surface, and this resulted in considerably greater inclination at the root of the cutter-tooth. The writer had found inclined faces very successful in the case of end mills where practically the whole of the cutting was done by the outer edges.

In the case of clutch mills the writer had found some difficulty in obtaining these properly made in high-speed steel. The clutches should be made with radial segments of even number and each segment should carry two, three or other finite number of complete teeth, as shown in Fig. 22. The arrangement shown in Fig. 23 was to be avoided as it usually gave some weak teeth in the first instance, and the conditions became worse if the cutter was to be re-cut.

Aluminium and other soft materials could be advantageously worked by cutters of high-speed steel, a high finish being readily obtainable, but clogging would result if the gaps between the teeth were not sufficiently large. The writer had found cutters with inserted teeth, Fig. 24, gave the best results for this class of work, as these readily permitted of giving variation in the clearance angle. Fig. 25 showed a high-speed steel cutter for rounding the sides of the teeth of automobile gear-wheels, and Fig. 26 showed a milling cutter for roughing the teeth of bevel gears preparatory to their being finished on the bevel shaping machine.

The PRESIDENT wrote, giving the following results of his experience in the locomotive workshops of the Taff Vale Railway. Milling cutters made with clean straight-cut teeth, and used at a cutting speed generally adopted, were very liable to chatter, owing to the full cut touching the work at such regular intervals. This form of tool must be used at a comparatively slow cutting speed and reduced feed to avoid the finished work being serrated; therefore, a clean, straight-cut tooth milling cutter was not satisfactory. Neither was profiling with mitre cutters quite a success, because the cutting speed had to be regulated according to the largest diameter of mitre cutter, and the pitch of cutter teeth was always too coarse at the top or too fine at the bottom, and because of its mitre shape the teeth must be straight cut. It was also rather difficult for an unskilled machinist, when grinding a mitre tool, to keep it to the angle required. It was therefore more economical in the majority of cases to set up the work to the required angle than to attempt milling with angular cutters.

So far as the cutting properties of a milling tool were concerned, the angle at the back of the cutting edge was of very little importance. It should be regarded more in the nature of a clearance angle, and as affecting the strength of the tooth and the life of the sharp edge. That the least possible clearance, so as to ensure the free contact of cutting edge only, was sufficient was clearly demonstrated in the cutting properties of taps and solid dies. Milling with facing cutters was an extravagant method of removing metal, as the bulk of the work had to be done with the extreme point of tooth.

Another form of cutter much used was made up with a soft metal hub and teeth of small section steel fixed to hub centre in various ways. This style of tool was often a saving in first cost only; the loss of time in using a fine feed demanded by the coarse pitch of cutter teeth, even in the best makes, and the amount of metal removed, having to be done by a lesser number of teeth, were considerable, more so when the time occupied to unstrip, sharpen, and re-adjust the separate cutters, was taken into account.

(The President.)

The best and most satisfactory form of milling cutter for general work and for all metals was the spiral step-tooth style, making the longitudinal spiral pitch relative to depth and not of a universal or standard character. For wrought-iron and mild steel cutters up to 3 inches diameter, 8 teeth per inch diameter was a good proportion, but, for the purpose of recutting the cutters with as little waste as possible, it was sometimes advisable to have 6 teeth per 1 inch diameter of cutter. The spiral twist had to be made left-handed, so that the lead of cut took place at the spindle end of machine; this tended to force the spindle hard against the thrust centre, provided on all well-made milling machines, for adjustment of spindle cone and curling the shavings from top to bottom, thus allowing the lubricant to have a free flow directly on to that part of tool in operation. The spiral twist must be regulated so as to give a slight lead to the tooth cutting at the top as the following tooth was just leaving the bottom, thus avoiding any tendency to chatter. The front cutting angle should lead from periphery of tool to a point behind the centre equal to  $\frac{1}{10}$  of its diameter, or  $12^\circ$  with a back clearance angle of  $3^\circ$ , making a cutting angle of  $75^\circ$ .

For cast-iron the cutter should be of a somewhat coarser pitch, owing to the slower cutting speed and the front angle diverting to the centre; the back clearance should be about the same as for wrought-iron.

For brass and white-metal lined articles the same provisions should be made as for wrought-iron, except that the front cutting angle should be slightly in advance of the centre. This was not because the cutting qualities were improved by this less acute angle, but because it was the best method to keep the tool free from clogging. It shortened the curl of shaving and so removed it from the tool as soon as it was made; otherwise much time was wasted in stopping the machine to free the cutter from shavings jammed in the teeth.

When cutters were intended to be used in combination due consideration should be given to the direction of spiral twist, as the success of milling with a series of cutters, or in combination of

shapes, depended largely on the free delivery of shavings. The direction of spiral, angle of front cutting, pitch and twist, should be considered with a view of helping the tools to free themselves from clogging and overheating wherever a step or hollow might be forming.

Dr. ASHTON wrote from Palermo, in reply to the written communications, that he was acquainted with the merits of the electrically-heated bath (page 1057). It was, however, expensive unless used for very large quantities of tools, and more advantageous for heavy than for small cutters such as dealt with at Enfield, where also the practice of hardening rifle components in large numbers wholly or partially made it convenient to employ the same means for tool-hardening, as a large number of workmen were experienced in their use.

Mr. Goodchild's remarks as to the cooling were also particularly applicable to cutters in which the total body of metal was large in proportion to the size of the teeth. There was no doubt that different methods would be suitable to cutters of different proportions. He (the author) thought he had avoided laying down any generalizations for other work than of the class with which he specifically dealt.

As regards the methods of backing-off and sharpening, he must differ positively from Mr. Goodchild's deductions from his experience and report of former experiments in the direction of the system in use at Enfield. The ordinary backing-off lathe could not deal at all with most of the cutters used, and the system described dealt better with the remainder. The high-speed steel no doubt held its edge longer than ordinary steel, and if the tool were kept really sharp the small amount to be ground off gave no trouble in respect of the reduction in size in the grinding wheel of the special material used and within the limits of accuracy of the best interchangeable work. Mr. Goodchild's generalizations were, he thought, too broad.

Mr. Legros' experience was interesting, and his remarks were generally confirmatory of the author's results, particularly in his

(Dr. Ashton.)

reference to the maxim "keep sharp," the object of the system described, and the essence of its effective use.

The President's remarks (page 1063) were chiefly applicable to the plainer forms of milling cutters, but not to complicated profiles.

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Fig. 2. *Hardening Furnace and Pyrometer.*

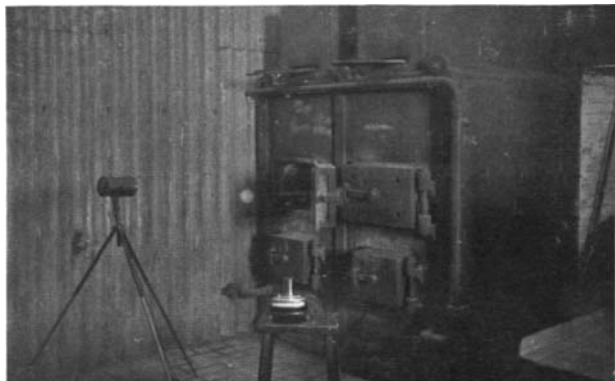


Fig. 4.

*Backing-off Cutter-Teeth, with Tracing-pin and Former.*

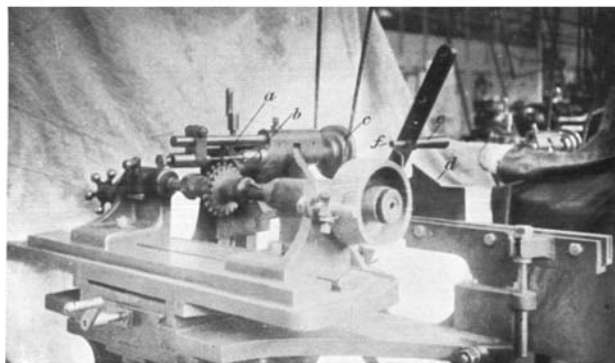


Fig. 3. *Air-Hardening Table.*

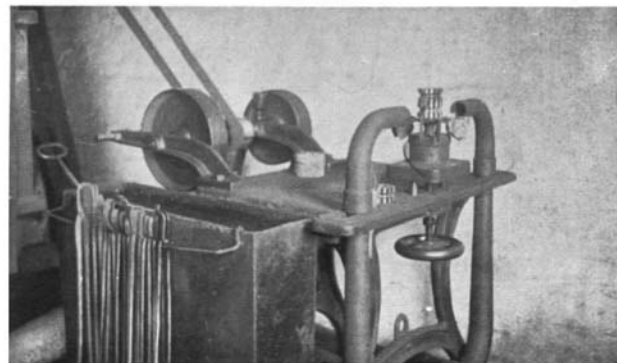


Fig. 5.

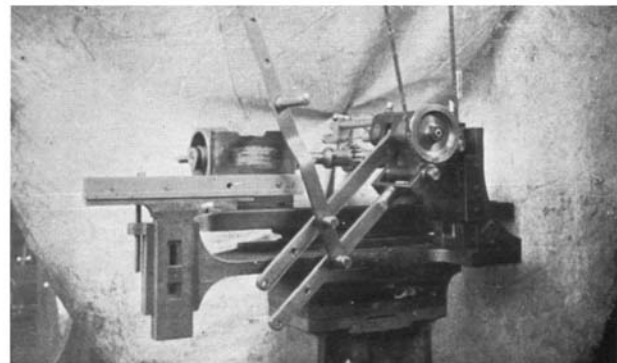
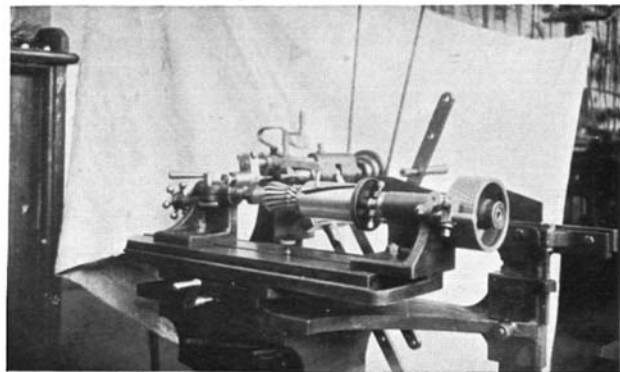
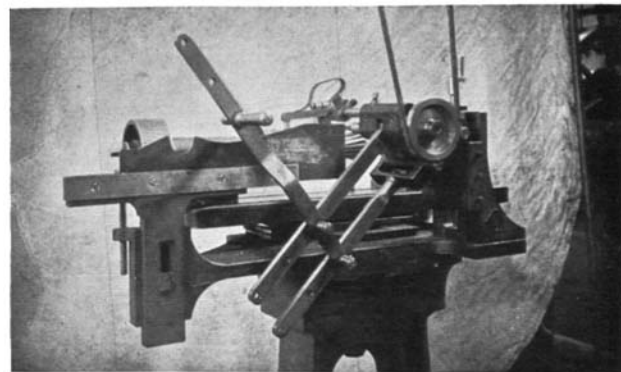


Fig. 6.



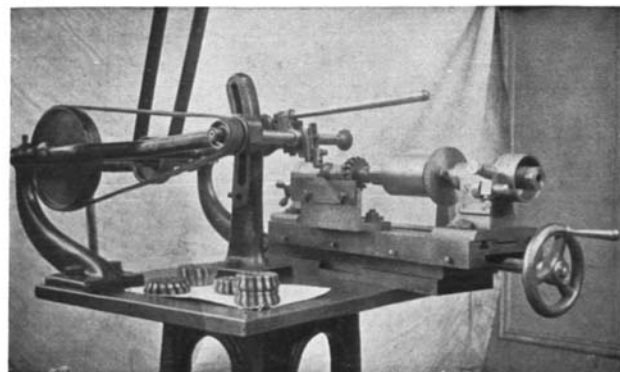
*Backing-off Cutter-Teeth, using a Spiral Slot.*

Fig. 7.



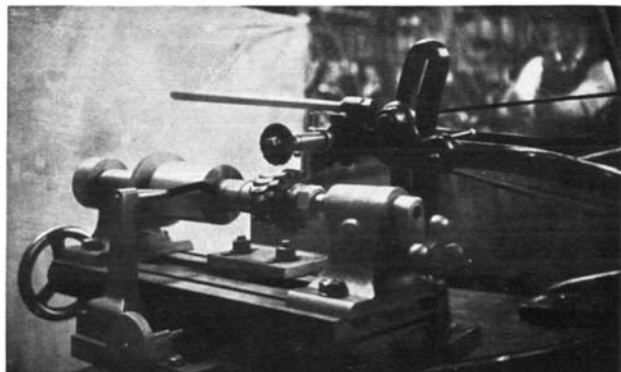
Pl.84.

Fig. 8.



*Grinding Cutters.*

Fig. 9.



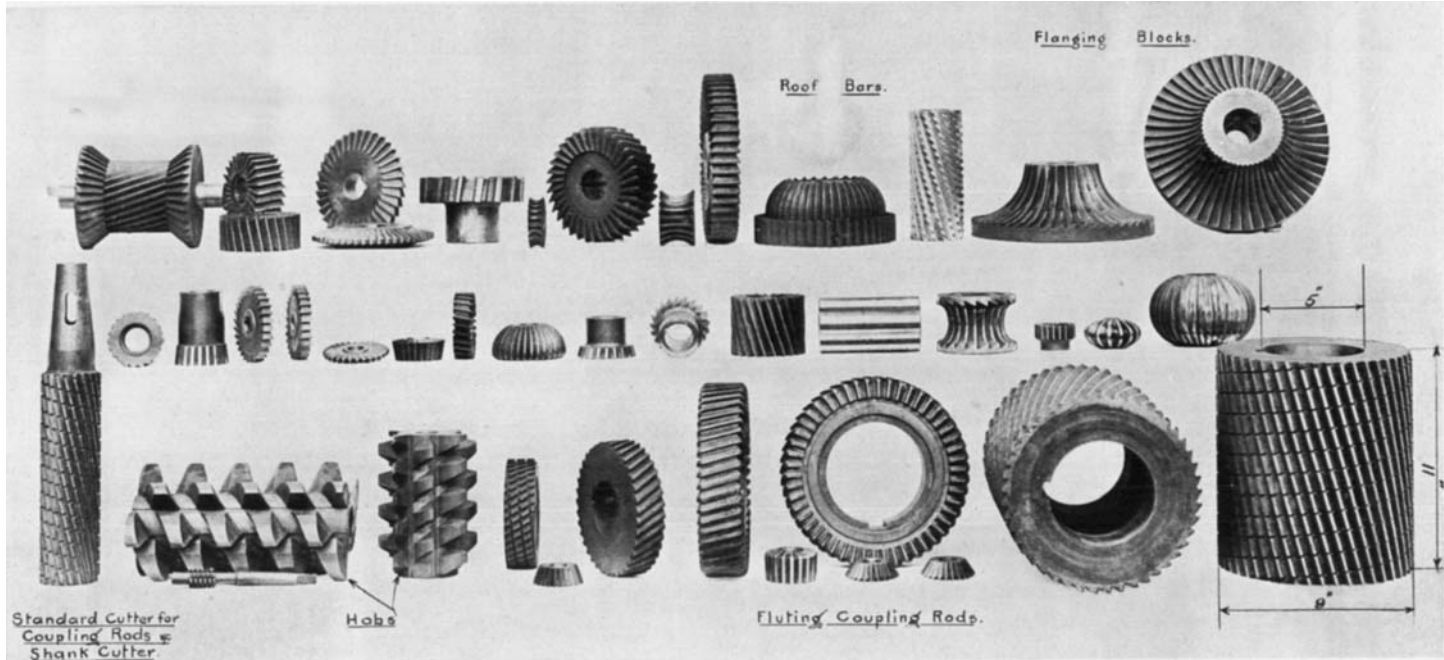


# MILLING CUTTERS.

Plate 85.

*Mr. George Hughes' remarks.)*

Fig. 10. *Specimens of Milling Cutters etc., used at Horwich.*



(Mr. Walter Carter's remarks. Figs. 12 to 16.)

Fig. 12. Muffle Furnace for hardening milling cutters, etc.

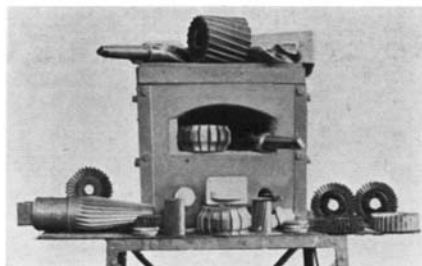


Fig. 13. Tempering Tank and Cage used with Fig. 12.



Fig. 14. Hob, 5 1/2 in. diam. made of High-Speed Steel.

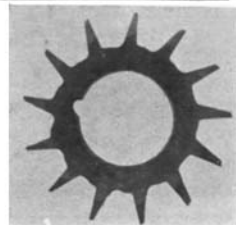
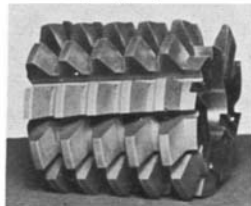


Fig. 16. Vertical Cutter with inserted teeth, milling hard chrome Steel. Speed, 75' per min. Feed, 16" per hour. Cut, 3 1/4" deep by 2 3/8" wide.

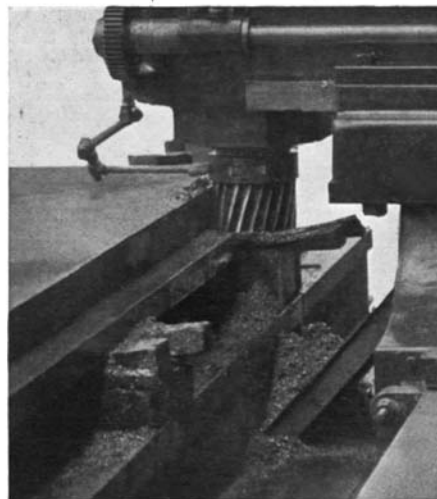
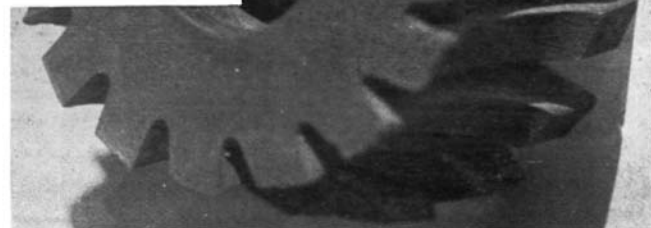


Fig. 15. High-Speed Steel Gear-Cutter after cutting 100,000 teeth.



(Author's reply.)

Fig. 27. Cutter as removed from Hardening Furnace.

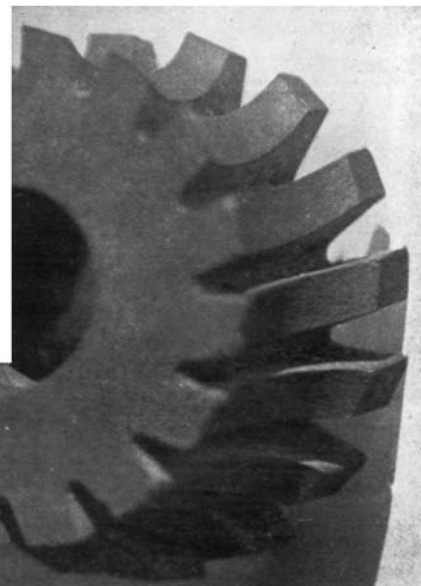


Plate 86.

MILLING CUTTERS.

Plate 86.